Indonesian Journal of Earth Sciences, Vol. 03, No. 2 (2023), 770

P-ISSN: 2798-1134 | E-ISSN: 2797-3549 | DOI: 10.52562/injoes.2023.770

Indonesian Journal of Earth Sciences

https://journal.moripublishing.com/index.php/injoes

| Research Article |

Check for updates

Soil Quality Indicators under Different Smallholder Managed Cropping and Landuse Practices in Abuja, Nigeria

Safirat Sani, Sani Abubakar Mashi *, Clement Didi Chup

Department of Geography and Environmental Management, University of Abuja, PMB 117, Abuja, Nigeria

** Correspondence: abubakar.sani@uniabuja.edu.ng*

Received: 26 June 2023 / Accepted: 02 December 2023 / Published: 29 December 2023

Abstract: There are limited reports about the impacts of smallholder-managed cropping and land-use practices (CLUPs) on soil quality, especially in developing countries. This study investigates the impact of six different Cropping Land Use Practices (CLUPs) on soil quality parameters in Abuja, Nigeria, focusing on sesame mono-cropping (SM), guinea corn mono-cropping (GCM), yam mono-cropping (YM), maize + yam mixed cropping (MYM), maize mono-cropping (MM), and natural forest (NF). The objectives are to determine Soil Organic Carbon (SOC), Total Nitrogen (TN), and pH values in the six CLUPs and assess differences under various CLUPs and soil depths. The study conducted in the University of Abuja Permanent Site, covers 11,000 hectares and analyzes soil samples from three replicate plots per CLUP, considering topsoil (0-15cm) and subsoil (20-30cm). The results indicate slightly acidic soils with low SOC and TN contents. Significant differences in SOC, TN, and C/N ratio are observed among cropping systems, with mixed cropping (MYM) promoting higher SOC. The C/N ratio is consistently low across CLUPs, indicating accelerated decomposition. While intra-plot soil heterogeneity is low, significant declines in soil quality indicators are noted under cropping systems compared to the natural forest. The study recommends site-specific, sustainable land management practices tailored to each cropping system. Encouraging organic matter additions, such as using animal and farmyard manure, is proposed to enhance soil fertility and reverse degradation trends. The findings contribute to understanding how diverse cropping practices impact soil quality, providing valuable insights for sustainable land management in the Abuja region.

Keywords: soil, quality parameters, landuse, cropping practices, smallholder farmers

INTRODUCTION

Soil is important not only for human survival but also for the overall health of ecosystems around the world. This means that human progress will be most successful if it gets enough attention. For food production, its primary operational function is to offer nourishment to plants and absorb and drain water. Consequently, the FAO (Food and Agriculture Organization) of the United Nations declared in the first revised World Soil Charter that "soils are a crucial enabling resource, central to the generation of a variety of commodities and services integral to ecosystems and human well-being" (FAO, 2015). To derive the services and benefits that soil could offer, different cropping and landuse practices (CLUPs) are being established and managed in different parts of the world (Lal, 2010 & 2015; Yang et al., 2020).

The term "soil quality" is used to refer to a soil's capacity to sustain human requirements, nourish plants, and maintain and improve soil air and water quality (Chandel et al., 2018; Gayan et al., 2020; Jiang et al., 2020). Increasing research evidences from around the world show that soil quality is declining under various CLUPs at a time when global efforts to achieve the SDGs are increasing (Kiflu & Beyene, 2013; Zajicová & Chuman, 2019; Adebo et al., 2020; Assefa et al., 2020; Laekemariam & Kibret, 2020; Hussain et al., 2021).

Numerous studies have been carried out to assess changes in soil quality resulting from different landuse practices using a variety of indicators (see, for instance, Islam & Weil, 2000; Ezeaku, 2015; Bünemann et al., 2018; Doğan & Gülser, 2019; Kongor et al., 2019; Mulyono et al., 2019; Sefati et al., 2019; Nguemezi et al., 2020; Amoakwah, 2021; Kaur et al., 2021; Mulat et al., 2021; Nath et al., 2021; Saleh et al., 2021; Silvianingsih et al., 2021). Changes in soil indicators and other metrics can be used to quantify soil quality changes brought about by different CLUPs of which the use of soil organic carbon (SOC), total nitrogen (TN), and soil reaction (pH) represent the three most common ones (Pham, 2010; Pham et al., 2018a; Vashisht et al., 2020; Wang et al., 2021). According to Chen et al. (2010), SOC is essential to soil fertility and serves as a reliable measure of a soil's biological health as well as its chemical, biological, and physical processes. In particular, crop growth is limited when SOC levels are low in the soil (Kay & Angers, 1999). It is well known that SOM (upon which SOC is based) increases structural stability, improves resistance to rainfall impact, holds a significant amount of nutrients, cations, and trace elements that are essential to plant growth, accelerates infiltration and faunal activity, prevents nutrient leaching, is essential to organic acids that make nutrients accessible to plants while serving as a soil buffer to resist significant changes in pH, and is a key component in the overall quality of soil. The effects of land use change on total nitrogen in soil have been studied (Roose & Barthes, 2001; Yerima & van Ranst, 2005; Leu, 2007). SOC level is constantly changing because it is a product of a balance between two highly dynamic processes of organic material input into soil (such as through amendments using crop waste, plant roots, and animal dung) on the one hand, and on the other, losses through declines in amounts of plant and animal materials, surface erosion, litter oxidation, and microbial breakdown in soil. The primary nutrient essentially needed for vegetative development is TN (Ren et al., 2014), while one of the most crucial soil factors and a necessity for agricultural output is soil pH, as most agricultural crops grow best in soil that has a pH between 5.5 and 6.5 (Havlin et al., 1999).

In the literature, substantial research information is available on the effects of various CLUPs on SOC, TN, and pH, but the findings across different landscapes are still controversial. Many researchers (for example, Abbasi et al., 2007; Abad et al., 2014; Takele et al., 2014; Bore et al., 2015; Dengiz et al., 2015; Kalu et al., 2015; Chemada et al., 2017; Olorunfemi et al., 2018; Galindo et al., 2022; Paramesh et al., 2022; Shi et al., 2010; Wang et al., 2021; and Hota et al., 2022) observed that paddy rice had a higher SOC content than forested soil, while Jonczak (2013) found out that fallow land had a higher SOC content than forested soil. Pham et al. (2018b), on the other hand, found that soils under planted acacia and rubber forest covers and arable land had higher SOC levels than those under natural forest, while Mengistu et al. (2022) observed that the SOC values of soils under cropland and *Eucalyptus camaldulensis* planted fallows are not significantly different from each other. Kebebew et al. (2022) discovered that soils near natural forests had lower SOC levels than those under Enset (*Ensete ventricosm)* planted fallow. Chen et al. (2016) found that TN in croplands was markedly lower than in wooded land; however, Moges et al. (2013) contended that TN did not exhibit any substantial difference across all CLUPs. Yet, Lizaga et al. (2019) found out that TN levels of natural forest were higher than those of cropland but only slightly different from those of planted fallow and shrubland. Studies have also found that different CLUPs have differential impacts on soil pH as well (for instance, Fayissa et al., 2015; Khormali & Shamsiv, 2014; Lizaga et al., 2019). According to Liu et al. (2018), while farmland had a higher SOC value than orchard and grassland, grassland had a higher TN value than both orchard and farmland, but the pH levels of the three plots were very slightly different. Manpoong et al. (2019) observed that while natural forests had higher levels of SOC and TN than planted forests (rubber, bamboo, and oil palm) and bush fallow, pH was not significantly different among the plots. Tellen & Yerima (2019) discovered that while SOC is highest in virgin forest, Eucalyptus plantations, virgin savanna, and grazing land, it is lowest in afforested parkland savanna. TN was observed to be highest under virgin savanna and grassland, followed by virgin forest, then arable farmland and Eucalyptus plantations, and least under afforested parkland. In terms of pH, the highest levels were found in virgin savanna and grazing land, followed by planted parkland savanna, then virgin forest, and finally farmland, which had the lowest levels.

The examples above imply that similar management practices can have different effects on soil quality in different ecosystems. Beside management practices, spatial elements such as topographic aspect, location, and climatic circumstances have a big impact on soil qualities (Ovalles & Collins, 1986; Pausas et al., 2007; Tesfahunegn et al., 2020). Because these things are different from one place to the next, it follows that the soil in each area needs to be looked at in its own context to figure out how many quality problems are caused by its use and what the best solution is to fix these problems. Despite the large volume of literature on the effects of CLUPs on OC, TN, and pH soil quality indicators, there is very limited research information on it for smallholder-managed CLUPs in West Africa, even though the region accounts for about 15% of the farming population in the world.

It follows from the above that soil play critical role in sustaining human life and maintaining ecosystem health as well as the ability to meet human needs, support plant growth, and maintain overall soil health. The fact that soil heath deteriorates under cropping and landuse practices despite the many attempts being made towards achieving Sustainable Development Goals (SDGs) globally no doubts sets the stage for the research gap that needs to be examined in areas under continuous cropping practices. This creates a research imperative, given the importance of soil for agriculture, ecosystem health, and human well-being. It is also clear that there is a somewhat controversy and inconsistency in research findings across different landscapes on soil quality deterioration due to cropping. The examples provided, such as the differing effects of paddy rice and fallow land on SOC content, contribute to the rationale for the study and this particularly reinforces the need for more localized and context-specific studies. Additionally, the influence of spatial elements like topography, location, and climate on soil quality, further justifying the need for site-specific investigations. One best way to assess soil quality changes is by referencing key indicators such as Soil Organic Carbon (SOC), Total Nitrogen (TN), and soil pH. These indicators are crucial for understanding the biological, chemical, and physical processes of soil. The choice of these indicators is rationalized based on their widespread use and relevance in assessing soil quality changes.

This study hence makes a contribution in this regard by examining the effects of six different CLUPs, namely sesame (*Sesamum indicum*) mono (SM) cropping, guinea corn (*Sorghum bicolor*) mono (GCM) cropping, yam (*Dioscorea rotundata*) mono cropping (YM), maize (*Zea mays L.*) + yam mixed (MYM) cropping, maize mono-cropping (MM), and natural forest (NF), on SOC, TN, and pH values of soils in Abuja, Nigeria. The major objectives of the study are to determine the content of SOC, TN, and pH values of the six CLUPs, and examine the differences in SOC, TN, and pH under the different CLUPs and soil depths.

The study's significance is underscored by its focus on smallholder-managed CLUPs in West Africa, a region representing a substantial portion of the global farming population. The dearth of research in this region despite its agricultural importance highlights the research gap that the study aims to address. The six CLUPs chosen for investigation in Abuja, Nigeria, represent a diversity of agricultural practices, adding relevance to the study.

METHOD

Study Area

The study area (University of Abuja Permanent Site, latitude $8^{0}55^{1}$ - $9^{0}14^{1}$N and longitude $6^{0}51^{1}$ - $7^{0}11^{1}$E, Figure 1) covers about 11,000 ha (118 km^2) of land and serves as an excellent testing ground for the type of investigation intended in this study because its climatic, geologic, topographic, and landuse histories are fairly uniform. The area typically experiences a tropical savanna climate. There are distinct wet and dry seasons. The wet season usually occurs from April to October, with the peak rainfall between June and September. The dry season spans from November to March. Abuja generally has high temperatures, with relatively cooler conditions during the rainy season. Abuja has an elevation that varies, contributing to the city's relatively cooler climate compared to some other parts of Nigeria. The topography is characterized by undulating plains and hills, typical of the central part of Nigeria. Generally speaking, the landscape is flat to undulating with slope angles under 1^{0}. The area is underlain by granite gneiss and migmatite basement complex rocks, which have produced loamy sand and sand clay loam soils with low to moderate erodibility and run-off potential. These soils are deep and well-drained.

Although there is a long (8-month) rainy season in the area, June through September each year sees roughly 60% of the region's total annual rainfall of about 2000 mm. The natural vegetation in the region is influenced by the tropical climate. Savanna vegetation with grasses and scattered trees is common. A little under 42% of the region is made up of parkland savanna woodland (most of it protected), 36% is farmed, 9% is covered in mixed grass shrubs (used for grazing), 5% is built up, 7% is made up of granitic hills, and 1% is covered in drainage. Farming activities are undertaken on a smallholder basis, with per capita land ownership averaging about 0.5 ha. Tillage operations are carried out using a hoe (for weeding and planting) and an ox-driven plough (for making ridges). Soil fertility is maintained using inorganic fertilizers, with superphosphate, urea, and NPK (20:10:10) being the main ones used. The major crops grown include sesame (*Sesamum indicum),* guinea corn (*Sorghum bicolor*), yam (*Dioscorea rotundata),* and maize (*Zea mays L.*). Weedicides are occasionally used by the farmers to control highly persistent weeds in the area. Abuja is a planned city, designated as the capital in the 1980s to replace Lagos. The city is organized into various districts, each serving specific purposes such as residential, commercial, and administrative. The University of Abuja Permanent Site constitutes an integral part of the city's land use, contributing to the educational and research landscape of the region.

Sampling Design and Selection of Sampling Plots

The study adopted an inferential approach to soil change assessment which presupposes that soils of an area which is fairly uniform in terms of climatic, geological, and topographic/geomorphic characteristics will differ in their characteristics mainly due to the variations in the landuse and cropping practices they are subjected to (Abubakar, 1997). Using the approach an area was identified within Abuja, located at the permanent site of the University of Abuja due to its uniform climatic, geologic, and topographic characteristics which made it suitable for the investigation intended in the study. The soils of the area are subjected to five cropping practices (namely (sesame mono cropping (SM), guinea corn mono cropping (GCM), yam mono cropping (YM), maize + yam mixed cropping (MYM), maize mono cropping (MM)) which are representative of the main ones undertaken in the Abuja area. A sixth plot (landuse) is under long standing natural forest cover which was chosen to serve as the control based upon whose condition the changes in soils of the five cropping practices could be assessed.

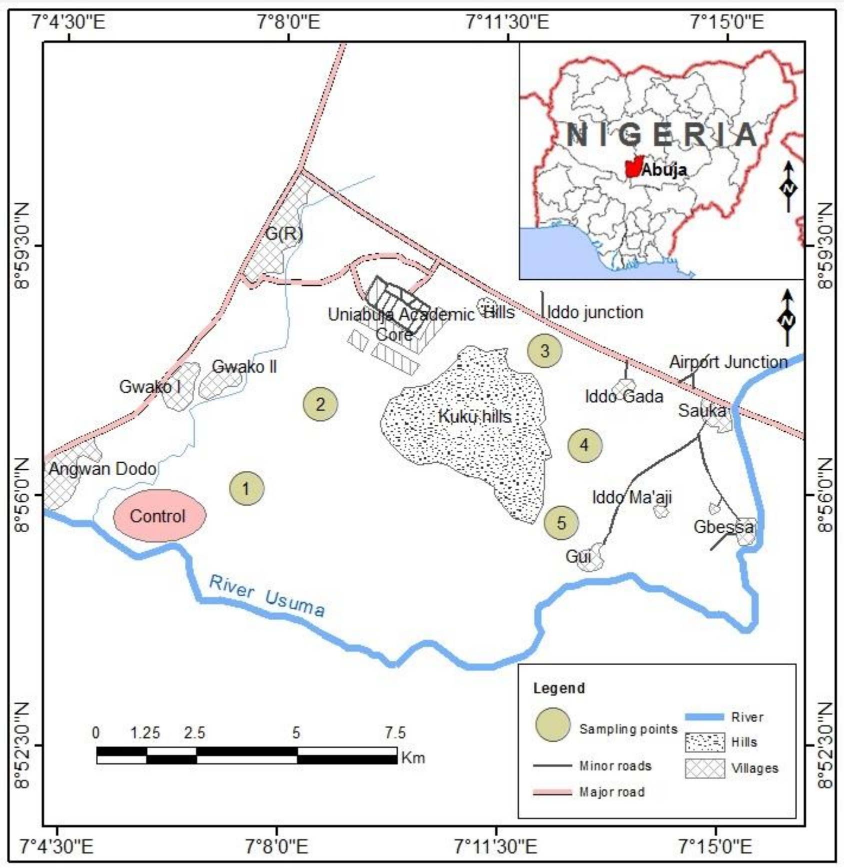

Figure 1. Study area showing location of soil sampling points

Soil Samples Collection

For each of the six plots, three replicate sampling sub-plots of 10 m x 10 m dimension each were marked and chosen for soil samples collection to ensure sampling reliability. In each CLUP in the study area, three replicate sampling plots with a 10 m x 10 m dimension were chosen. Each sampling sub-plot was divided into 16 grid squares of identical size, and soil samples were collected from two standard depths in the middle of each grid square (0-15 cm for topsoil and 20-30 cm for subsoil) using a core sampler. This enabled collection of 96 core samples for each CLUP plot (16 topsoil samples x 3, plus 16 subsoil samples x 3), resulting in a total of 576 samples (96 samples x 6) for the six CLUPs, giving a total of 576 samples (96 samples x 6) for the 6 CLUPs. Sampling at these two depths was undertaken to ensure comparability between the six plots. The collected samples were transported to the laboratory under controlled conditions to preserve their integrity for analyses.

Soil Analyses

While in the laboratory, the collected were kept at 4 degrees Celsius for further routine analytical process testing. The samples were air-dried and ground to pass through a 0.5-mm sieve to remove gravel-sized fractions. 10g sub-sample was then collected from each sieved sample for detailed analysis. For soil organic carbon, Walkley-Black oxidation method was used (Anderson & Ingram, 1993). Potassium dichromate-sulfuric acid mixture. The mixture was heated to oxidize organic carbon and the remaining dichromate titrated after which the organic carbon values were calculated. To determine soil pH, soil-water and soil-$CaCl_2$ suspensions were prepared at a ratio of 1:2.5 each. To each prepared suspension, an electrode of a pH meter, which was calibrated with a standard buffer solution, was inserted after which the suspension was allowed to stabilize before readings were taken. To determine total nitrogen, Kjeldahl digestion method was used (Anderson & Ingram, 1993). The soil sub-sample was digested with concentrated sulfuric acid and then neutralized with sodium hydroxide. The ammonia produced from the neutralized solution was then distilled and captured in a boric acid solution. The excess acid was then titrated with a standard sodium hydroxide solution.

Statistical Analyses

The mean and standard error of the mean values were computed for every property for both topsoil and subsoil for every CLUP plot. An analysis of variance (ANOVA) and t-test were used to test for significant differences in values of the analyzed soil properties. Analysis of Variance (ANOVA) and t-test are statistical methods that play crucial roles in soil data analysis, providing valuable insights into the variation and significance of different factors. ANOVA is particularly useful when dealing with multiple groups or treatments (e.g., different land uses, fertilizer applications). It helps determine if there are significant differences in means among the groups, such as assessing the impact of different land management practices on soil pH or nutrient levels. T-test is used comparing the means of two groups (e.g., treated vs. untreated soil). It helps in determining if difference between two means is statistically significant. For example, comparing soil organic carbon levels between fertilized and unfertilized plots. The two tests are thus essential tools in soil data analysis, allowing researchers to draw meaningful conclusions about the factors influencing soil properties. They contribute to evidence-based decision-making in agriculture, environmental science, and land management by helping identify significant differences, assess treatment effects, and understand the variability in soil data. The student's t-test was used in this study to test for significant differences in mean values of the soil properties between the two sampling depths. The test was also used to test for significant differences between the mean values of every property for the NF plot on the one hand and each of the five cropping plots (SM, GCM, MM, MYM, and YM) on the other. ANOVA test was conducted in this study to examine the significance of differences in mean values of the soil properties in the five cropping system plots. The tests were carried out at 0.05 probability level.

RESULTS & DISCUSSION

Table 1 shows the mean and standard error of the mean for the three soil quality parameters that were measured in both the topsoil and the subsoil in the study area, which had a natural forest as the control and five cropping practices as the other groups. The tables also show the summary of t-test analyses conducted to compare the mean values of the various properties between the topsoil and subsoil layers with a view to identifying the specific properties on which the CLUPs have caused significant changes between the two layers. It also shows a summary of the ANOVA test, which was used to compare the mean values of the different properties across the five cropping practices in order to find the set of properties that were most affected by the practices in the study area.

Variation in Soil Properties between Topsoil and Subsoil

In general, Table 1 shows that pH values between topsoil and subsoil are not significantly different. However, the two biological properties (SOC and TN) and the C/N ratio are in general significantly higher in the topsoil than the subsoil, perhaps reflecting the higher organic activities of the upper soil layer, which favor higher topsoil levels of those soil properties. Organic matter makes soils have more biological activity, so it's not surprising that the two properties were found to be higher in the topsoil (Jobbágy & Jackson, 2001; Iqbal et al., 2014; Guan et al., 2015; Chen et al., 2016).

In the literature, a number of measures have been identified as those capable of promoting accumulation of organic materials in the topsoil layer, and such include retention and incorporation of crop residue back into the soil (Fu et al., 2001; Antle & Stoorgovel, 2008), use of animal manure (Irfan et al., 2021), incorporation of farmyard manure (Ahmad et al., 2021; Mebrate, 2022), and use of biosolids derived from waste dumpsites (Pampana et al., 2021). Farmers in the study area don't do a good job of taking care of their animals, so they don't have much animal manure to use on their farms. The use of biosolids from dumpsites is not common among farmers, while much of the crop residue is removed from the farmlands after harvest to be used in feeding livestock kept at home and also used as an energy source for domestic cooking. These things suggest that the soils in the area don't have a lot of organic matter, which means they don't have a lot of SOC or TN.

Table 1. Mean and standard error of the mean values of SOC, TN, C/N ration and pH under the 6 CLUPs

Soil Property	Sampling Depth (cm)	Values for the Various CLUPs											
		Natural Forest		Yam		Sesame		Yam + Maize		Maize		Guinea Corn	
pH 1:2.5 (H_2O)	0-15	6.89	0.12	5.64*	0.13	5.78*	0.1	5.76*	0.06	5.86*	0.13	5.85*	0.25
	20-30	6.27	0.29	5.31*	0.23	5.64*	0.23	5.39*	0.25	5.62*	0.31	5.47*	0.4
	DBMSD	NS		NS		NS		NS		NS		NS	
pH 1:2.5 ($CaCl_2$)	0-15	6.61	0.11	5.95*	0.18	5.87*	0.16	6.03*	0.08	6.36	0.16	5.95*	0.25
	20-30	5.32	0.32	5.83*	0.33	5.69	0.22	5.96	0.23	6.03*	0.28	5.73*	0.45
	DBMSD	NS		NS		NS		NS		NS		NS	
Soil Organic Carbon (g/kg)	0-15+	0.95	0.32	0.62*	0.25	0.22*	0.04	0.41*	0.61	0.32*	0.31	0.27*	0.15
	20-30+	0.49	0.34	0.23*	0.24	0.06*	0.02	0.28*	0.14	0.24*	0.03	0.13*	0.05
	DBMSD	S		S		S		S		S		S	
Total Nitrogen (g/kg)	0-15+	0.24	0.02	0.12*	0.01	0.07*	0.02	0.15*	0.01	0.19*	0.02	0.14*	0.02
	20-30+	0.19	0.02	0.08*	0.01	0.03*	0.01	0.06*	0.01	0.03*	0.01	0.02*	0.01
	DBMSD	NS		S		S		S		S		S	
C/N Ratio	0-15+	3.05	0.73	5.16*	0.68	3.14	0.52	2.73*	0.62	1.68*	0.25	1.93*	0.14
	20-30+	2.57	0.54	1.14*	0.42	2.00*	0.39	4.67*	0.32	8.0*	0.11	6.50*	0.05
	DBMSD	NS		S		S		S		S		S	

Note:

a. The asteriks (*) denotes the mean values for the cropping plots that are significantly different from that of the control; as revealed by t-test analysis at 0.05 probability level.
b. DBMSD = Differences between mean values of soil properties of the two sampling depths, being significant (S) or not significant (NS); as revealed by t-test analysis at 0.05 probability level.
c. The plus (+) sign indicates the sampling depth at which means values of the soil properties are statistically different amongst the five cropping plots; as revealed by ANOVA test at 0.05 probability level.

Influence of Cropping Practices on Intra-plot Spatial Heterogeneity

Spatial heterogeneity in soil properties over a specific plot is typically assessed by computing the coefficient of variation (CV%) or standard error of the mean (SEM) values of every soil property (Mao et al., 2014; Zajícová & Chuman, 2019; Sun et al., 2022). Typically, CV% values less than 25% are considered low, while those greater than 25% are considered high; however, when CV% values exceed 25% but are less than 50%, the heterogeneity is considered moderate, while values greater than 50% are considered high. Where SEM values are computed, values that are less than 25% of the various mean values are regarded as indicators of low spatial heterogeneity, while those that are above 25% but less than 50% of the mean values are regarded as indicators of moderate heterogeneity, and those above 50% of the mean values are regarded as indicators of high heterogeneity.

A close look at Table 1 revealed that the SEM values of the three soil quality indicators under both the control and cropping plots are generally less than 25% of the mean values, which suggests that the practices have not caused much intra-plot soil heterogeneity in the study area. A possible reason for this is the very low variation in slope angle, as the plots generally have very low variation in slope angle (less than 10 slopes on average). Higher variation in slope angle typically results in differentials in processes such as slope wash, nutrient loss, and organic matter oxidation that influence the distribution of soil properties over a given plot (Moges & Holden, 2008; Wubie & Assen, 2020).

Soil Quality Variation between the Control and the Cropping Plots

The differences in mean values of the various soil quality parameters between the control and cropping systems are, in general, statistically significant, with the values for the control being higher than those of the cropping systems. This indicates that the establishment of cropping systems has caused some degradation in the quality of the soils in the cropping systems in the study area. Lower SOC and TN of the cropping plots are attributable to less plant residue being produced and incorporated into the soils as cultivation cycles progress, a high rate of oxidation of litter materials, and livestock browsing the residues left on farmlands in the area. Cultivation is well known to promote declines in organic matter levels unless measures are adopted to bring about the incorporation of organic residues into the cultivated soils (Solly et al., 2020). Above- and below-ground crop residue retention and integration in cultivated soils have been shown to contribute towards raising SOC levels significantly above those of forested soil (Liu et al., 2011; Li et al., 2014; Pham et al., 2018b). In the study area, unfortunately, all of the crop residue is shipped away from the farms to be used to feed the animals that farmers keep in their homes and to heat their homes.

Soil Quality Variation over the Five Cropping Plots

Table 1 also shows that the average values of the different soil properties are very different between the five cropping plots, both in the topsoil and in the subsoil. This means that the cropping practices in the study area have caused soil heterogeneity.

Soil Reaction (pH)

It has been shown that pH is directly or indirectly related to soil moisture, salinity, nutrient availability, and many other soil characteristics (Lüneberg et al. 2018; Lynn et al. 2017). The soil pH levels in the area range from 5.5 to 6.5 (moderately acidic), and soil reaction that is close to neutral is regarded as quite favorable for plant growth because P availability will be optimal under such conditions (Oku et al., 2021). Bationo et al. (2003) have shown that the pH of savanna soils is, in general, moderately to slightly acidic (5.5 to 6.9) and quite favorable for plant growth.

The topsoil pH values range from 5.87 to 6.86 for sole cropping and 6.76 for mixed cropping. In the subsoil, the values range from 5.31 to 6.03 for the sole cropping plots and 5.96 for the mixed cropping plot (Table 1). This indicates that the mixed cropping system promoted a higher pH level in the soils of the study area, and a possible reason for this is the fact that mixed cropping promotes greater vegetation cover and consequently less risk of slope wash, which could otherwise lower the levels of base elements as sheet erosion occurs. The results also showed that though soil pH is significantly lower under the cropping plots than the control, the values did not vary significantly between the five cropping systems, indicating that the cropping systems have a similar effect on the decline in property values in the area. Abbasi et al. (2007), Kiflu & Beyene (2013), and Liao et al. (2015) have variously observed that pH varied significantly with landuse types, while other researchers (Rokunuzzaman, et al., 2016 and Moges et al., 2013) observed that the property did not vary with landuse types, as was found out in this study

Going by the classification of Landon (1991), the pH values of the five cropping plots can be rated as being slightly acidic, which could most probably be a reflection of the parent material (granitic rocks) that gave birth to the soils of the study area. Tellen & Yerima (2019) describe the chemical fertilizers and weedicides used for soil fertility maintenance in the area as typically containing some high amounts of cations, which could help to balance out the negative charges lost from the soil's exchange complex of cultivated soils as losses occur due to processes such as sheet erosion induced by high tillage and weeding frequencies and low organic matter in the control and the five cropping plots. The range in value of the property in the study area is not very wide, with the lowest being about 5.3 and the highest being about 6.9; however, the fact that the pH values of the cropping plots are significantly lower than those of the control is an indication of the fact that losses of cations have been occurring from the soils of the cultivated plots, which is very much in agreement with the findings of many research workers (Sadiq et al., 2021; Tumayro & Tesgaye, 2021; Haile et al., 2022; Hota et al., 2022). This suggests that where effective soil fertility amendments are introduced, declines in pH level cannot only be minimized but even be reversed. Kizilkaya & Dengiz (2010) have reported a significant increase in the pH of cultivated soils in Turkey that have been receiving applications of organic manure, mulching, crop rotation, and limited tillage. In areas receiving liming amendments in Vietnam, soil pH was found by Pham et al. (2018b) to have increased significantly under arable crop farming. Farmers cultivating acidic soil have been reported to add up to 500 kg of lime per hectare to increase acidic soil productivity (Rengel, 2003; Ha, 2003; Hoang & Le, 2012; Nduwumuremyi et al., 2013).

Organic Carbon

In most tropical soils, clay minerals are largely low-activity types, especially kaolinite, with low capacities to fix CEC and hold nutrients. Organic matter is consequently the main colloidal source that undertakes such activities (Sanchez, 2019). In addition, the colloid serves as the major source of much of the native nitrogen and phosphorous in soils. It also serves as an energy source for soil microorganisms, reduces erosion, and improves soil texture and structure (Arunrat et al., 2020). It is therefore a very important property for plant nutrition.

Soil organic carbon (SOC) levels of less than 2g/kg are rated as low (Udo et al., 2009). In smallholder farms, crop residues are rarely left on the farmlands after harvest, and even where they are, they undergo rapid oxidation and mineralization due to solar heating, aggressive browsing by livestock, and collection for use as a domestic fuel source (Oku et al., 2017). Adiaha (2017) has shown that in tropical farming environments, the general addition of organic residues, which determines the organic matter content in the soil, is low while the loss of such residues through mineralization is high. The low SOC rating of soils in the study area is not surprising given that tropical savanna soils have been widely reported to be sandy in texture, low in organic matter due to a combination of low vegetation cover, a high rate of litter oxidation, decomposition, and mineralization due to solar heating, livestock browsing of standing vegetation and crop leftovers, and a low level of use of organic amendments in soil fertility maintenance (Kizilkaya & Dengiz, 2010; Sanchez, 2019). When soils are put into cultivation, an imbalance is created between organic material inputs and outputs through the above sources of loss, which makes carbon stocks unstable and highly vulnerable to decline (Guo & Gifford, 2002; Wiesmeier et al. 2012). However, due to the application of organic amendments, Liu et al. (2011), Li et al. (2014), and Pham et al. (2018a) discovered that arable land has a higher SOC content than forested land.

The results obtained in this study showed that SOC significantly varied with the cropping practices in both soil layers. The five cropping plots have significantly lower levels of organic carbon and total nitrogen than the control. The mean values of the property for the control plot at the topsoil and subsoil were 0.95 g/kg and 0.49 g/kg while for the cropping plots, the values in the upper soil layer range between 0.22 g/kg under sesame sole cropping and 0.62 g/kg under yam sole cropping. The trend in the lower layer is similar to that of the upper layer (Table 1). These suggest that the five cropping systems have caused a significant decline in OC level, and the most probable reason for this is that farmers in the study area do not incorporate crop residue in soil fertility maintenance as nearly all the stubble is exported out of the farmlands at the time of harvest. SOC varied significantly with land use, according to Boivin et al. (2009) and Wubie & Assen (2020).

The results obtained also revealed that the mixed-cropping systems have comparatively higher SOC values than the sole cropping systems. The high content of the property of mixed cropping plots is perhaps a reflection of greater plant cover during the cropping period. Kumar et al. (2019) have shown that practices involving the cultivation of more than one crop (in mix or rotation forms) could increase the input of OC in the soil, which could promote higher N availability, leading to enhanced soil fertility. Also, Aula et al. (2016) found out that nitrogen application significantly increased SOC content when the rate exceeded 90kg per hectare due to the stimulation of increased growth of cover crops that contribute to above- and below-ground organic material levels in soils. A study by Zhang et al. (2016) has shown that incorporation rates of 15%, 50%, and 90% of crop residue resulted in increases in SOC levels of 78 kg/ha/yr, 489 kg/ha/yr and 1005 kg/ha/yr respectively. Also, increased biomass production due to irrigation practices has been shown to have contributed to increased additions of SOC and TN in cultivated soils (Halvorson & Schlege, 2012).

Total Nitrogen

Total nitrogen (TN) levels in soils of between 0.5 g/kg and 1.0 g/kg are regarded as high and a desirable level (Oku et al., 2021). In the study area, while the control plot had TN levels of 0.24 and 0.19 for the topsoil and subsoil, respectively, the values for the cropping systems range between 0.12 mg/kg (under YM) and 0.19 mg/kg (under MM) in the topsoil, and in the subsoil, the property varied between 0.02 mg/kg (under GM) to 0.08 (under YM). These show that the soils of the study are inherently low in native TN, as even the control plot has values that are well below the required level. The generally lower TN values of soils in the study area may be a reflection of the low values of property in the soils of the Nigerian savanna, which are related to the sandy nature and low net return of litter to the soils from standing vegetation in the region (Jones & Wild, 1975). It could be seen that the pattern of TN distribution over the cropping plots in the study area is similar to that of TOC. This is partly expected because organic matter serves as the major source of TN in soils (Sanchez, 2019).

The mean values of the property are significantly different amongst the five cropping systems, which indicates that the cultivation practices have resulted in significant TN heterogeneity in the study area. The results of the t-test comparing the mean TN values of the control plot with those of each of the five cropping systems showed that the cropping systems maintained significantly lower levels of the property than the control, indicating that the systems have caused a significant decline in levels of the property in the soils of the study area. The significant decline in TN levels in the cropping systems could be related to the rapid mineralization of the organic substrates derived from root biomass following intensive cultivation and the removal of crop residue from farmlands after harvest in the study area (Oku, et al., 2021).

In different ecosystems, it has been seen that clearing vegetation and setting up roping practices cause C and N levels in the soil to drop significantly if no effort is made to add more organic material to the soil (Mustapha, 2007; Chemada et al., 2017; Tufa et al., 2019). Where, for instance, livestock are allowed to stay on cultivated land during the off-farming season, their dung and urine will be adding nutrients, humus, seeds, and microbes that could help stimulate vegetation, regeneration as well as improve soil structure and nutrients' fertility levels, and these could turn the farmland into a nutrient hotspot. Recent research findings in Zimbabwe have shown that the organic matter added to the soil in this way can last up to five years (Dube-Matutu, 2022). Liu et al. (2014) in China and Rodríguez-Murillo (2001) found that cultivation resulted in a significant decline in TN levels, while Emiru & Gebrekidan (2013) in Ethiopia, Li et al. (2016) in China, and Pham et al. (2018a) in Vietnam found that cultivated soils receiving applications of N-rich mineral fertilizers have TN levels that are significantly higher than those of forest lands.

C/N Ratio

C and N are the two primary elements involved in plants' growth and development, and the ratio between them is an indicator of nitrogen mineralization ability and use efficiency, and a key input parameter for some ecological and ecosystem models aimed at evaluating soil biological productivity (Zhang et al., 2020). It is therefore a sensitive indicator of soil quality. The soil C/N ratio is usually considered an indicator of soil nitrogen mineralization ability. High C/N ratios in soils can retard the rate of organic matter and organic nitrogen decomposition by limiting the ability of soil microbial actions, whereas low C/N ratios in soils could accelerate the process of microbial decomposition of organic matter and nitrogen (Yerima & van Ranst, 2005; Tellen a& Yerima, 2018). However, Wu et al. (2001) reported that a low soil C/N ratio is not conducive to carbon sequestration. In general, values that are less than 10 are considered to be poor indicators of soil quality, while 10 is regarded as the optimum. Deng et al. (2013) pointed out that the greatest organic matter mineralization in soils would occur at a substrate C:N ratio of 25. If the ratio is less than 20, mineral N is released in the early stages of the decomposition process because the dividing line between the immobilization and release of N is about 20:1 (Swangjang, 2015). Thus, values between 10 and 20 can be regarded as desirable for crop productivity.

Relationship of the Study Findings to the Research Problem and Literature

The results obtained showed that the mean C/N ratio values of the various CLUPs in the study area were less than 6, implying that the quality is low. The values varied significantly between the five cropping systems, with the values all significantly lower than those of the control, indicating that the practices have caused significant declines in the mean values of the property. It can thus be concluded that the soils under the CLUPs in the area are promoting accelerated decomposition of organic matter and limiting the rate of mineralization of organic nitrogen by reducing soil microbial activity. Because of this, their ability to store carbon will be limited, and they can't be counted on to be the only way to fight climate change.

In general, the findings align with literature emphasizing the role of organic inputs in maintaining soil fertility. pH decline due to cultivation resonates with studies highlighting the impact of land use on soil properties. The results obtained showed no significant difference in pH between topsoil and subsoil. Topsoil had significantly higher levels of SOC and TN, indicating higher organic activity. Practices like retaining crop residue and using organic amendments were identified as factors promoting organic matter accumulation in topsoil. Low spatial heterogeneity observed in both control and cropping plots. Low variation in slope angle likely contributed to uniformity in soil properties. Coefficient of variation (CV%) and standard error of the mean (SEM) values generally below 25%, indicating low heterogeneity. The control plot had significantly higher mean values for soil quality parameters compared to cropping plots. Cropping practices led to degradation, with lower SOC and TN attributed to reduced organic residue incorporation and high oxidation of litter materials. Significant differences in soil properties among the five cropping plots, both in topsoil and subsoil.

Soil pH slightly acidic, favorable for plant growth. Mixed cropping promoted higher pH levels, possibly due to increased vegetation cover reducing slope wash. Generally low SOC levels, attributed to factors such as low vegetation cover and removal of crop residue. Mixed-cropping systems showed higher SOC values, possibly due to increased plant cover during cropping. Inherently low native TN levels in study area soils. Cropping systems significantly decreased TN levels, linked to intensive cultivation and crop residue removal. Low C/N ratio values (< 6) suggest low soil quality. Cropping practices significantly reduced C/N ratios, indicating accelerated organic matter decomposition and limited nitrogen mineralization. Lack of organic matter inputs (e.g., crop residues) in the study area contributed to low SOC and TN levels. The practice of removing crop residue for livestock and energy needs negatively impacted soil quality. The cropping systems induced significant variations in soil properties, emphasizing the need for sustainable practices. Mixed cropping showed some benefits, potentially due to increased plant cover and diverse crop residues. pH decline in cropping plots suggests cation losses, highlighting the need for effective soil fertility management. Soil amendments could mitigate pH decline, emphasizing the importance of targeted interventions. Low spatial heterogeneity suggests relatively uniform soil properties.

CONCLUSION

The study compared soil quality parameters in both topsoil and subsoil across a natural forest (control) and five cropping practices (CLUPs) in the study area. While pH values did not significantly differ between topsoil and subsoil, organic properties (SOC and TN) and the C/N ratio were significantly higher in the topsoil, suggesting higher organic activities in this layer. The absence of significant differences in pH between cropping practices indicates a relatively stable soil reaction across the study area. Spatial heterogeneity within plots, assessed by the coefficient of variation (CV%) and standard error of the mean (SEM), was generally low, suggesting that CLUPs had not induced significant intra-plot soil heterogeneity. Low variation in slope angle was identified as a potential factor contributing to the observed low heterogeneity.

Significant differences in mean values of soil quality parameters were observed between the control and cropping systems, with the control plots generally exhibiting higher values. Cropping practices led to significant degradation in soil quality, particularly in terms of SOC and TN levels. Significant differences were noted in the average values of soil properties among the five cropping plots, indicating that cropping practices have induced soil heterogeneity in the study area.

The soil pH ranged from 5.5 to 6.5 (moderately acidic), with mixed cropping promoting higher pH levels. Despite the overall pH values being within a favorable range for plant growth, the decline in pH under cropping plots compared to the control suggests cation losses and soil degradation. SOC levels were significantly lower in cropping plots compared to the control, indicating a decline in organic matter due to practices such as the removal of crop residue from farmlands. Mixed cropping systems demonstrated higher SOC values, emphasizing the potential benefits of diversified cropping practices for soil health. TN levels were generally low, with cropping systems maintaining significantly lower levels than the control. The rapid mineralization of organic substrates and the removal of crop residue were identified as factors contributing to the decline in TN levels. The C/N ratio values were below 6, indicating poor soil quality. Significant declines in C/N ratio values under cropping systems suggest accelerated decomposition of organic matter and reduced soil microbial activity.

It is recommended that the farmers be encouraged to adopt practices that promote the retention and incorporation of crop residue into the soil, such as mulching and cover cropping. There is a need to promote the use of organic amendments, including animal manure and biosolids, to enhance soil organic matter content. There is also the need to advocate for diversified cropping systems, including mixed cropping, to enhance vegetation cover, reduce slope wash, and minimize soil degradation. Emphasis should also be given to sustainable soil fertility practices in the area, such as the use of organic fertilizers, to maintain nutrient levels and prevent declines in soil pH. Soil conservation measures, such as contour plowing, to address potential soil erosion issues need to be particularly promoted. There is an equal need to promote advocacy for the development and implementation of government policies that incentivize sustainable agricultural practices and soil conservation efforts. Awareness programs to educate farmers on the importance of soil conservation practices and the long-term benefits of maintaining soil health need to also be conducted. Local communities need to be engaged in participatory soil management programs to ensure the adoption of recommended practices and the sustainability of soil health initiatives. Research is needed to monitor soil properties and assess the effectiveness of the recommended practices over time. By implementing these recommendations, it is anticipated that soil health and fertility in the study area can be improved, contributing to sustainable agriculture and environmental conservation.

ACKNOWLEDGEMENT

This work is based on postgraduate research undertaken by the first named author under the direction and supervision of the second and third named authors, in the Department of Geography &

Environmental Management of the University of Abuja, Abuja, Nigeria. Thanks are due to the academic staff of the department for their various inputs at the various stages of the work. The people who worked in the soil science lab at Ahmadu Bello University in Zaria, Nigeria, are thanked for their part in analyzing the soil samples in the lab.

DATA AVAILABILITY STATEMENT

The data that this study was based on can be gotten from the first author if you ask nicely.

REFERENCES

Abad, J. R. S., Hassan, K. & Alamdarlou, E. H. (2014). Assessment the effects of land use changes on soil physicochemical properties in Jafarabad of Golestan province, Iran. *Bulletin of Environment, Pharmacology and Life Sciences, 3*(3), 296-300.

Abbasi, M. K., Zafar, M. & Khan, S. R. (2007). Influence of different land-cover types on the changes of selected soil properties in the mountain region of Rawalakot Azad Jammu and Kashmir. *Nutrient Cycling in Agroecosystems, 78*(1), 97-110. https://doi.org/10.1007/s10705-006-9077-z

Abubakar, S. M. (1997). Monitoring land degradation in the semiarid tropics using an inferential approach: the Kabomo basin case study, Nigeria. *Land degradation & Development, 8*(4), 311-323. https://doi.org/10.1002/(SICI)1099-145X(199712)8:4%3C311::AID-LDR262%3E3.0.CO;2-8

Adebo, B. O., Aweto, A. O., & Ogedengbe, K. (2020). Assessment of soil quality under different agricultural landuse systems: a case study of the Ibadan Farm Settlement. *International Journal of Plant & Soil Science, 32*(4), 89-104. https://doi.org/10.9734/IJPSS/2020/v32i430275

Adiaha, M. S. (2017). The role of organic matter in tropical soil productivity. *World Scientific News, 86*(1), 1-66.

Ahmad, S., Ghaffar, A., Ur Rahman, M. H., Hussain, I., Iqbal, R., Haider, G., Khan, M. A., Ikram, R. M., Hussain, H., & Bashir, M. S. (2021). Effect of application of biochar, poultry and farmyard manures in combination with synthetic fertilizers on soil fertility and cotton productivity under arid environment. *Communications in Soil Science and Plant Analysis, 52*(17), 2018-2031. https://doi.org/10.1080/00103624.2021.1908324

Amoakwah, E., Rahman, M. A., Nketia, K. A., Djouaka, R., Didenko, N. O. & Islam, K. R. (2021). Impact of deforestation and subsequent land-use change on soil quality. *Eurasian Journal of Soil Science, 10*(2), 150–160. https://doi.org/10.18393/ejss.843861

Anderson, J. M., & Ingram, J. S. I. (Eds.). (1993). *Tropical Soil Biology and Fertility: A handbook of methods.* 2nd Edition. Wallingford: CAB International.

Antle, J. M., & Stoorvogel, J. J. (2008). Agricultural carbon sequestration, poverty and sustainability. *Environmental and Development Economics, 13*(3), 327–352. https://doi.org/10.1017/S1355770X08004324

Arunrat, N., Kongsurakan, P., Sereenonchai, S., & Hatano, R. (2020). Soil organic carbon in sandy paddy fields of northeast Thailand: A Review. *Agronomy, 10*(8), 1061. https://doi.org/10.3390/agronomy10081061

Assefa, F., Elias, E., Soromessa, T. & Ayele, G. T. (2020). Effect of changes in landuse management practices on soil physico-chemical properties in Kabe Watershed, Ethiopia. *Air, Soil and Water Research, 13*, 1–16. https://doi.org/10.1177/1178622120939587

Aula, L., Macnack, N., Omara, P., Mullock, J., & Raun, W. (2016). Effect of fertilizer nitrogen(N) on soil organic carbon, total N, and soil pH in long-term continuous winter wheat (*Triticu maestivum* L.). *Communications in Soil Science and Plant Analysis Journal, 47*(7), 863–874. https://doi.org/10.1080/00103624.2016.1147047

Bationo, A., Mokwunye U., Vlex, P. L. P., Koala, S., & Shapiro, B. I. (2003). Soil fertility management for sustainable landuse in the West African Sudano-Sahelian zone. In: Gichuru, M. P., Bationo, A., Bekunda, M. A., Goma, H. C., Mafongonya, P. L., Mugendi, N., Murwira, H. M., Nandwa, S. M., Nyathi, P., & Swift, M. J. (Eds). *Soil Fertility Management in Africa: A regional perspective.* Academy Science Publishers (ASP), 253-292.

Boivin, P., Schaffer, B., & Sturny, W. (2009). Quantifying the relationship between soil organic carbon and soil physical properties using shrinkage modeling. *European Journal of Soil Science, 60*(4), 265–275. https://doi.org/10.1111/j.1365-2389.2008.01107.x

Bore, G. & Bedadi, B. (2015). Impacts of land use types on selected soil physico-chemical properties of Loma Woreda, Dawuro Zone, Southern Ethiopia. *Science, Technology and Arts Research Journal, 4*(4), 40-48. https://doi.org/10.4314/star.v4i4.6

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goedeb, R., Fleskensd, L., Geissend, V., Kuyper, T. W., Mädera, P., Pulleman, M., Sukkelf, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality - a critical review. *Soil Biology and Biochemistry, 120*, 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030

Chandel, S., Hadda, M. S., & Mahal, A. K. (2018): Soil quality assessment through minimum data set under different landuses of submontane Punjab. *Communications in Soil Science and Plant Analysis, 49*(6), 658-674. https://doi.org/10.1080/00103624.2018.1425424

Chemada, M., Kibret, K. & Fite, T. (2017). Influence of different land use types and soil depths on selected soil properties related to soil fertility in Warandhab Area, Horo Guduru Wallaga Zone, Oromiya, Ethiopia.

International Journal of Environmental Sciences and Natural Resources, 4(2), 555634. https://doi.org/10.19080/IJESNR.2017.04.555634

Chen, C. P., Juang, K. W., Cheng, C. H., & Pai, C. W. (2016). Effects of adjacent land-use types on the distribution of soil organic carbon stocks in the montane area of central Taiwan. *Botanical Studies Journal*, *57*, 32-46. https://doi.org/10.1186/s40529-016-0147-5

Deng, Q., Cheng, X., Zhou, G., Liu, J., Liu, S., Zhang, Q., & Zhang, D. (2013). Seasonal responses of soil respiration to elevated CO_2 and N addition in young subtropical forest ecosystems in young subtropical forest ecosystems in Southern China. *Ecological Engineering*, *61*, 65-73. https://doi.org/10.1016/j.ecoleng.2013.09.063

Dengiz, O., Sağlam, M., & Türkmen, F. (2015). Effects of soil types and landuse-land cover on soil organic carbon density at Madendere watershed. *Eurasian Journal of Soil Science, 4*(2), 82–87. https://doi.org/10.18393/ejss.64398

Doğan, B. & Gülser, C. (2019). Assessment of soil quality for vineyard fields: A case study in Menderes District of Izmir, Turkey. *Eurasian Journal of Soil Science, 8*(2), 176–183. https://doi.org/10.18393/ejss.551874

Doran, J. W., Coleman, D. C., Bezdicek, D. F., & Stewart, B. A. (1994). Defining soil quality for a sustainable environment. *Soil Science Society of America Journal*, *61*(1), 4–10.

Dube-Matutu, S. (2022). Scholar turns cow dung into "gold" for farmers, rural folk. Available online at: https://www.chronicle.co.zw/scholar-turns-cow-dung-into-gold-for-farmers-rural-folk/. Accessed 9th December 2022.

Elias, E., Biratu, G. K., & Smaling, E. M. A. (2022). Vertisols in the Ethiopian Highlands: interaction between landuse systems, soil properties, and different types of fertilizer applied to Teff and Wheat. *Sustainability, 14,* 7370. https://doi.org/10.3390/su14127370

Emiru, N., & Gebrekidan, H. (2013). Effect of land use changes and soil depth on soil organic matter, total nitrogen and available phosphorus contents of soils in Senbat Watershed, Western Ethiopia. *ARPN Journal of Agricultural and Biological Science*, *8*(3), 206-212.

Ezeaku, P. I. (2015). Evaluation of agro-ecological approach to soil quality assessment for sustainable land use and management systems. *Scientific Research and Essays, 10*(15), 501-512. https://doi.org/10.5897/SRE10.404

FAO (Food and Agricultural Organisation). (2015). *Revised World Soil Charter*. FAO, Rome. Available Online at: https://www.fao.org/documents/card/en/c/e60df30b-0269-4247-a15f-db564161fee0/. Accessed 23rd July 2021.

Fayissa, A., Ababaew, A., & Chimdi, A. (2015). Effects of different landuses (forest, grazing and cultivated) on the fertility status of acidic soils of Dano district, West Shoazone, Oromia region, Ethiopia. *American-Eurasian Journal of Scientific Research, 10*(4), 235–242.

Fu, B., Chen, L., Huang, H., Qu, P., & Wei, Z. (2021) Impacts of crop residues on soil health: a review. *Environmental Pollutants and Bioavailability, 33*(1), 164-173. https://doi.org/10.1080/26395940.2021.1948354

Galindo, V., Giraldo, C., Lavelle, P., Armbrecht, I., & Fonte, S. J. (2022). Land use conversion to agriculture impacts biodiversity, erosion control, and key soil properties in an Andean watershed. *Ecosphere, 13*, e3979. https://doi.org/10.1002/ecs2.3979

Gayan, A., Nath, D. J., Bhattacharyya, B. & Dutta, N. (2020). Assessment of soil quality indicators under rice ecosystem of Assam, India. *Journal of Environmental Biology, 41,* 1655-1664. https://doi.org/10.22438/jeb/41/6/SI-246

Guan, F., Tang, X., Fan, S., Zhao, J., & Peng, C. (2015). Changes in soil carbon and nitrogen stocks following the conversion from secondary forest to Chinese fir and Moso bamboo plantations. *Catena, 133*, 455–460. https://doi.org/10.1016/j.catena.2015.03.002

Guo, L. B., & Gifford, R. M. (2002). Soil carbon stocks and land use change. *Global Change Biology, 8*, 345–360. https://doi.org/10.1046/j.1354-1013.2002.00486.x

Ha, T. T. T. (2003). Effect of phosphorus fertilizer on groundnut yield in poor alluvial and sandy soils of Thua Thien Hue. *Better Crops International Journal, 17*(2), 16–17.

Haile, G., Itanna, F., Teklu, B., & Agegnehu, G. (2022). Variation in soil properties under different land use types managed by smallholder farmers in central Ethiopia. *Sustainable Environment, 8*(1), 2093058. https://doi.org/10.1080/27658511.2022.2093058

Halvorson, A. D., & Schlegel, A. J. (2012). Crop rotation effect on soil carbon and nitrogen stocks under limited irrigation. *Agronomy Journal, 104*(5), 1265-1273. https://doi.org/10.2134/agronj2012.0113

Havlin, J. L., Beaton, J. D., Tisdale, S. L., & Nelson, W. L. (1999). *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*. USA: Prentice-Hall Inc.

Hoang, T. T. H., & Le, H. L. (2012). Effects of nitrogen and potassium rates on peanut yield in coastal sandy soil of Binh Dinh province. *Journal of Science of Hue University, 71*(2), 133-144.

Hota, S., Mishra, V., Mourya, K. K., Giri, K., Kumar, D., Jha, P. K., Saikia, U. S., Prasad, P. V. V., & Ray, S. K. (2022). Landuse, landform, and soil management as determinants of soil physicochemical properties and microbial abundance of lower Brahmaputra Valley, India. *Sustainability, 14*, 2241. https://doi.org/10.3390/su14042241

Hussain, A., Ali, H., Begum, F., Hussain, A., Khan, M. A., Guan, Y., Zhou, J., Din, S. U., & Hussain, K. (2021). Mapping of soil properties under different landuses in lesser Karakoram Range, Pakistan. *Polish Journal Environmental Studies, 30*(2), 1181-1189. https://doi.org/10.15244/pjoes/122443

Iqbal, A., Hossen, S., & Islam, N. (2014). Soil organic carbon dynamics for different land uses and soil management practices in Mymensingh. In: *Proceedings of the 5th international conference on environmental aspects of Bangladesh*, pp.16–17.

Irfan, B. S., Kasal, Y., & Chowdary, D. M. (2021) A review on effects of chemical fertilizers and organic manures on soil fertility. *The Pharma Innovation Journal, 10*(8), 504-507.

Islam, K. R., & Weil, R. R. (2000). Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. *Agriculture, Ecosystems and Environment, 79*(1), 9–16. https://doi.org/10.1016/S0167-8809(99)00145-0

Jiang, M., Xu, L., Chen, X., Zhu, H., & Fan, H. (2020). Soil quality assessment based on a minimum data set: a case study of a county in the Typical River Delta Wetlands. *Sustainability, 12*, 9033. https://doi.org/10.3390/su12219033

Jobbágy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications Journal, 10*(2), 423–436. https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2

Jonczak, J. (2013). Soil organic matter properties in Stagnic Luvisols under different land use types. *Acta Agrophysica Journal, 20*(4), 565–576.

Jones, M. J., & Wild, A. (1975). *Soils of West African Savanna. The Maintenance and Improvement of Their Fertility*. Commonwealth Bureau of the Soils Technical Communication of the Harpenden. No. 55, UK Commonwealth Agricultural Bureau (CAB), Farnham Royal, 246.

Kalu, S., Koirala, M., Khadka, U. R., & Anup, K. C. (2015). Soil quality assessment for different landuse in the Panchase Area of Nepal. *International Journal of Environmental Protection, 5*(1), 38–43. https://doi.org/10.5963/IJEP0501006

Karlen, D. L., Andrews, S. S., Wienhold, B. J., & Zobeck, T. M. (2008). Soil quality assessment: past, present and future (2008). Publications from USDA-ARS / UNL Faculty. 1203. Available Online at: https://digitalcommons.unl.edu/usdaarsfacpub/1203. Accessed 16th March 2022.

Kaur, T., Sehgal, S. K., Singh, S., Sharma, S., Dhaliwal, S. S., & Sharma, V. (2021). Assessment of seasonal variability in soil nutrients and its impact on soil quality under different land use systems of lower Shiwalik Foothills of Himalaya, India. *Sustainability, 13*, 1398. https://doi.org/su13031398

Kay, B. D., & Angers, D. A. (1999). Soil structure. In: M.E. Sumner (Ed.), *Handbook of Soil Science* (pp. 229–276). Boca Raton, USA: CRC Press.

Kebebew, S., Bedadi, B., Erkossa, T., Fantaw, Y., & Wogi, L. (2020). Effects of different landuse types on soil properties in Cheha District, south-central Ethiopia. *Sustainability, 14*(3), 14031323. https://doi.org/10.3390/su14031323

Khormali, F., & Shamsiv, S. (2014). Effect of landuse on the carbon stock and soil quality attributes in Loess derived soils in Agh-Suwatershed, Golestan Province, Iran. *Environmental Resources Research Journal, 2*(2), 107–121.

Kiflu, A., & Beyene, S. (2013). Effects of different land use systems on selected soil properties in South Ethiopia. *Journal of Soil Science and Environmental Management, 4*(5), 100-107. https://doi.org/10.5897/JSSEM12.20

Kizilkaya, R., & Dengiz, O. (2010). Variation of land use and land cover effects on some soil physico-chemical characteristics and soil enzyme activity. *Zemdirb Agric, 97*(2), 15–24.

Kongor, J. E., Boeckx, P., Vermeir, P., van de Walle, D., Baert, G., Afoakwa, E. O., Dewettinck, K. (2019). Assessment of soil fertility and quality for improved cocoa production in six cocoa growing regions in Ghana. *Agroforestry System, 93*, 1455–1467. https://doi.org/10.1007/s10457-018-0253-3

Kumar, A., Naresh, R.K., Singh, S., Mahajan, N.C. & Singh, O. (2019). Soil aggregation and organic carbon fractions and indices in conventional and conservation agriculture under Vertisol soils of Sub-tropical Ecosystems: a review. *International Journal of Current Microbiology and Applied Sciences, 8*(10), 2236-2253. https://doi.org/10.20546/ijcmas.2019.810.260

Laekemariam, F., & Kibret, K. (2020). Explaining soil fertility heterogeneity in smallholder farms of southern Ethiopia. *Applied and Environmental Soil Science, 2020*, 1-16. https://doi.org/10.1155/2020/6161059

Lal, R. (2010). Managing soils to address global issues of the twenty- first century. In: *Food security and soil quality.* In: Lal, R & Stewart, A.B. (Eds). CRC Press, Taylor & Francis Group.

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability, 7*, 5875-5895. https://doi.org/10.3390/su7055875

Landon, J. R. (1991) *Booker tropical soil manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics.* Longman Scientific and Technical, New York.

Leu, A. (2007). Organics and soil carbon: increasing soil carbon, crop productivity and farm profitability. In: Managing the Carbon Cycle. Paper Presented at the Katanning Workshop, 21–22 March, 2007. Available Online at: http://www.amazingcarbon.com. Accessed 9th April 2022.

Li, Y., Han, J., Wang, S., Brandle, J., Lian, J., Luo, Y., & Zhang, F. (2014). Soil organic carbon and total nitrogen storage under different landuses in the Naiman Banner, a semi-arid degraded region of Northern China. *Canadian Journal of Soil Science, 94*(1), 9–20. https://doi.org/10.4141/cjss2013-074

Liao, W., Tang, D., Wang, X., & Cheng, X. (2015). Soil quality status of different landuse types in Shiqu County, China. *International Symposium on Energy Science and Chemical Engineering* (pp. 135–140). Atlantis Press. https://doi.org/10.2991/isesce-15.2015.27

Liu, D., Huang, Y., An, S., Sunc, H., Bhople, P., & Chen, Z. (2018). Soil physicochemical and microbial characteristics of contrasting land-use types along soil depth gradients. *Catena, 162*, 345–353. https://doi.org/10.1016/j.catena.2017.10.028

Liu, Z., Shao, M., & Wang, Y. (2011). Effect of environmental factors on regional soil organic carbon stocks across the Loess Plateau region, China. *Agriculture, Ecosystems & Environment Journal*, *142*(3–4), 184–194. https://doi.org/10.1016/j.agee.2011.05.002

Lizaga, I., Quijano, L., Gaspar, L., Ramos, M. C., & Navas, A. (2019). Linking land use changes to variation in soil properties in a Mediterranean mountain agroecosystem. *Catena, 172*, 516–527. https://doi.org/10.1016/j.catena.2018.09.019

Lüneberg, K., Schneider, D., Siebe, C., & Daniel, R. (2018). Drylands soil bacterial community as affected by land use change and different irrigation practices in the Mezquital Valley, Mexico. *Scientific Reports, 8*(1), 1-16. https://doi.org/10.1038/s41598-018-19743-x

Lynn, T. M., Ge, T., Yuan, H., Wei, X., Wu, X., Xiao, K., Kumaresan, D., Yu, S. S., Wu , J., & Whiteley, A. S. (2017). Soil carbon-fixation rates and associated bacterial diversity and abundance in three natural ecosystems. *Microbology and Ecolology, 73*, 645-657. https://doi.org/10.1007/s00248-016-0890-x

Manpoong, C. & Tripathi, S. K. (2019). Soil properties under different land use system of Mizoram, NorthEast India. *Journal of Applied and Natural Science, 11*(1), 121-125. https://doi.org/10.31018/jans.v11i1.1999

Mao, Q., Huang, G., Buyantuev, A., Wu, J., Luo, S., & Ma, K. (2014). Spatial heterogeneity of urban soils: the case of the Beijing metropolitan region, China. *Ecological Processes, 3*, 1-11. https://doi.org/10.1186/s13717-014-0023-8

Mebrate, A., Zeray, N., Kippie, T., & Haile, G. (2022). Determinants of soil fertility management practices in Gedeo Zone, Southern Ethiopia: logistic regression approach. *Heliyon, 8*, e08820. https://doi.org/10.1016/j.heliyon.2022.e08820

Mengistu, B., Amayu, F., Bekele, W., & Dibaba, Z. (2022). Effects of Eucalyptus species plantations and crop land on selected soil properties. *Geology, Ecology, and Landscapes, 6*(4), 277-285. https://doi.org/10.1080/24749508.2020.1833627

Moges, A., & Holden, N. M. (2008). Soil fertility in relation to slope position and agricultural landuse: a case study of Umbulo Catchment in southern Ethiopia. *Environmental Management, 42*, 753-763. https://doi.org/10.1007/s00267-008-9157-8

Moges, A., Dagnachew, M., & Yimer, F. (2013). Landuse effects on soil quality indicators: A case study of Abo-Wonsho Southern Ethiopia. *Applied and Environmental Soil Science, 9*, 784989. https://doi.org/10.1155/2013/784989

Mulat, Y., Kibret, K., Bedadi, B., & Mohammed, M. (2021). Soil quality evaluation under different land use types in Kersa sub-watershed, eastern Ethiopia. *Environmental Systems Research, 10*, 1-11. https://doi.org/10.1186/s40068-021-00224-6

Mulyono, A., Suriadikusumah, A., Harriyanto, R., & Djuwansah, M. R. (2019). Soil quality under agroforestry trees pattern in Upper Citarum Watershed, Indonesia. *Journal of Ecological Engineering, 20*(1), 203–213. https://doi.org/10.12911/22998993/93942

Mustapha, S. (2007). Physico-chemical properties and fertility status of some Haplic Plinthaquults in Bauchi local government area of Bauchi State, Nigeria. *International Journal of Tropical Agriculture and Food Systems, 1*(2), 314-315. https://doi.org/10.4314/ijotafs.v1i2.40900

Nath, C. P., Kumar, N., Das, K., Hazra, K. K., Praharaj, C. S., & Singh, N. P. (2021). Impact of variable tillage-based residue management and legume-based cropping for seven years on enzymes activity, soil quality index and crop productivity in rice ecology. *Environmental and Sustainability Indicators, 10*, 100107. https://doi.org/10.1016/j.indic.2021.100107

Nduwumuremyi, A., Ruganzu, V., Mugwe, J. N., & Rusanganwa, A. C. (2013). Effects of unburned lime on soil pH and base cations in acidic soil. *ISRN Soil Science, 2013*, 707569. https://doi.org/10.1155/2013/707569

Nguemezi, C., Tematio, P., Yemefack, M., Tsozue, D., & Silatsa, T. B. F. (2020). Soil quality and soil fertility status in major soil groups at the Tombel area, South-West Cameroon. *Heliyon, 6*, e03432. https://doi.org/10.1016/j.heliyon.2020.e03432

Oku, E. E., dos Passos, A. M. A., & Quintino, S. M. (2017). Soil fertility status and crop yields following the introduction of an intensive multiple cropping system in five villages in the upper east region of Ghana. *Review of Research Journal, 7*(3), 1-14.

Oku, E. E., dos Passos, A. M. A., Quintino, S.S., Odoh, N. C., & Olowookere, T. B. (2021). Soil fertility status of soils of sudano-sahelian and humid forest zones of west Africa and some soil management strategies for smallholder farms. *EQA - International Journal of Environmental Quality, 46*, 25-36. https://doi.org/10.6092/issn.2281-4485/12745

Olorunfemi, I. E., Fasinmirina, J. T., & Akinola, F. F. (2018). Soil physico-chemical properties and fertility status of long-term land use and cover changes: A case study in Forest vegetative zone of Nigeria. *Eurasian Journal Soil Science, 7*(2), 133–150. https://doi.org/10.18393/ejss.366168

Ovalles, F. A., & Collins, M. E. (1986). Soil-landscape relationships and soil variability in North Central Florida. *Soil Science Society of America Journal, 50*(2), 401–408. https://doi.org/10.2136/sssaj1986.03615995005000020029x

Pampana, S., Rossi, A., & Arduini, I. (2021) Biosolids benefit yield and nitrogen uptake in winter cereals without excess risk of N leaching. *Agronomy, 11*(8), 1482. https://doi.org/10.3390/agronomy11081482

Paramesh, V., Singh, S. K., Mohekar, D. S., Arunachalam, V., Misra, S. D., Jat, S. L., Kumar, P., Nath, A. J., Kumar, N., Mahajar, G. R., & Bhagat, T. (2022). Impact of sustainable land-use management practices on soil carbon storage and soil quality in Goa State, India. *Land Degradation and Development, 33*(1), 28-40. https://doi.org/10.1002/ldr.4124

Pausas, J. G., Casals, P., Camarero, L., Huguet, C., Sebastia, M. T., Thompson, R., & Romanya, J. (2007). Soil organic carbon storage in mountain grasslands of the Pyrenees: Effects of climate and topography. *Biogeochemistry Journal, 82*, 279–289. https://doi.org/10.1007/s10533-007-9071-9

Pham, T. G. (2010). Carbon in Vietnamese soils and experiences to improve carbon stock in soil. In: *Proceedings of International Workshop on Evaluation and Sustainable Management of Soil Carbon Sequestration in Asian Countries.* Bogor: Indonesia. Pp 175-186.

Pham, T. G., Degener, J., & Kappas, M. (2018a). Integrated universal soil loss equation (USLE) and Geographical Information System (GIS) for soil erosion estimation in ASapbasin: Central Vietnam. *International Soil and Water Conservation Research, 6*(2), 99-110. https://doi.org/10.1016/j.iswcr.2018.01.001

Pham, T. G., Nguyen, H. T., & Kappas, M. (2018b). Assessment of soil quality indicators under different agricultural landuses and topographic aspects in Central Vietnam. *International Soil and Water Conservation Research, 6*(4), 280-288. https://doi.org/10.016/j.swcr.2018.08.001

Ren, T., Wang, J., Chen, Q., Zhang, F., & Lu, S. (2014). The effects of manure and nitrogen fertilizer applications on soil organic carbon and nitrogen in a high-input cropping system. *PLoS One, 9*(5), e97732. https://doi.org/10.1371/journal.pone.0097732

Rengel, Z. (2003). *Handbook of Soil Acidity.* Marce Dekker, New York, 496 p.

Rodríguez-Murillo, J. C. (2001). Organic carbon content under different types of land use and soil in peninsular Spain. *Biology and Fertility of Soils, 33*, 53-61. https://doi.org/10.1007/s003740000289

Rokunuzzaman, M., Ueda, Y., Chen, L., Tanaka, S., & Ohnishi, K. (2016). Effects of land use changes from paddy fields on soil bacterial communities in a hilly and Mountainous area. *Microbes and Environments, 31*(2), 160–164. https://doi.org/10.1264/jsme2.ME15187

Roose, E., & Barthes, B. (2001). Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. In *Managing Organic Matter in Tropical Soils: Scope and Limitations: Proceedings of a Workshop organized by the Center for Development Research at the University of Bonn (ZEF Bonn)—Germany, 7–10 June, 1999 (pp. 159-170).* Springer Netherlands. https://doi.org/10.1007/978-94-017-2172-1_15

Sadiq, F. K., Maniyunda, L. M., Anumah, A. O., & Adegoke, K. A. (2021). Variation of soil properties under different landscape positions and land use in Hunkuyi, Northern Guinea savanna of Nigeria. *Environmental Monitoring and Assessment, 193*, 178. https://doi.org/10.1007/s10661-021-08974-7

Saleh, A. M., Elsharkawy, M. M., AbdelRahman, M. A. E., & Arafat, S. M. (2021). Evaluation of soil quality in arid western fringes of the Nile Delta for sustainable agriculture. *Applied and Environmental Soil Science, 2021*, 1-17. https://doi.org/10.1155/2021/1434692

Sanchez, P.A. (2019). *Properties and Management of Soils in the Tropics.* Cambridge: Cambridge University Press. https://doi.org/10.1017/9781316809785

Sefati, Z., Khalilimoghadam, B., & Nadian, H. (2019). Assessing urban soil quality by improving the method for soil environmental quality evaluation in a saline groundwater area of Iran. *Catena, 173*, 471–480. https://doi.org/10.1016/j.catena.2018.10.040

Shi, L., Zheng, L., Mei, X., Yu, L., & Jia, Z. (2010). Characteristics of soil organic carbon and total nitrogen under different landuse types in Shanghai. *The Chinese Journal of Applied Ecology, 21*(9), 2279-2287.

Silvianingsih, Y. A., Hairiah, K., Suprayogo, D., & van Noordwijk, M. (2021). Kaleka Agroforest in central Kalimantan (Indonesia): soil quality, hydrological protection of adjacent peatlands, and sustainability. *Land, 10*(8), 856. https://doi.org/10.3390/land10080856

Solly, E. F., Weber, V., Zimmermann, S., Waithert, L., Hagedon, F., & Schmidt, M. W. I. (2020). A critical evaluation of the relationship between the effective cation exchange capacity and soil organic carbon content in Swiss forest soil. *Frontiers in Forests and Global Change, 3*, 98. https://doi.org/10.3389/ffgc.2020.00098

Sun, G, Liu, H., Cui, D., & Chai, C. (2022). Spatial heterogeneity of soil nutrients in Yili River Valley. *Peer Journal of Life and Environment, 10*, e13311. https://doi.org/10.7717/peerj.13311

Swangjang, K. (2015). Soil carbon and nitrogen ratio in different landuse. *IPCBEE International Conference on Advances in Environment Research, 87*, 36-40. https://doi.org/10.7763/IPCBEE.2015.V87.7

Takele, L., Chimdi, A., & Abebaw, A. (2014). Dynamics of soil fertility as ınfluenced by different landuse systems and soil depth in West Showa Zone, Gindeberet District, Ethiopia. *Agriculture, Forestry and Fisheries, 3*(6), 489-494.

Tellen, V. A., & Yerima, B. P. K. (2019). Effects of landuse change on soil physicochemical properties in selected areas in the Northwest region of Cameroon. *Environmental Systems Research, 7*(1), 1-29. https://doi.org/10.1186/s40068-018-0106-0

Tesfahunegn, G. B., & Gebru, T. A. (2020). Variation in soil properties under different cropping and other land-use systems in Dura catchment, Northern Ethiopia. *PLoS ONE, 15*(2), e0222476. https://doi.org/10.1371/journal.pone.0222476

Tufa, M., Melese, A., & Tena, W. (2019). Effects of land use types on selected soil physical and chemical properties: The case of Kuyu District, Ethiopia. *Eurasian Journal of Soil Science, 8*(2), 94-109. https://doi.org/10.18393/ejss.510744

Tumayro, M., & Tesgaye, D. (2021). Impact of land use types and soil depths on selected soil physicochemical properties in Fasha District, Konso Zone, Southern Ethiopia. *Journal of Soil Science and Environmental Management, 12*(1), 10-16. https://doi.org/10.5897/JSSEM2020.0815

Udo, E. J., Ibia, T. O., Ogunwale, J. A., Ano, A. O., & Esu, I. E. (2009). *Manual of Soil, Plant and Water Analysis*, 1stEdition. Sidon Book Ltd, Lagos. Pp. 17 – 76.

Vashisht, B. B., Maharjan, B., Sharma, S., & Kaur, S. (2020). Soil quality and its potential indicators under different land use systems in the Shivaliks of Indian Punjab. *Sustainability, 12*(8), 3490. https://doi.org/10.3390/su12083490

Wang, H., Zhang, X., Wu, W., & Liu, H. (2021). Prediction of soil organic carbon under different landuse types using Sentinel-1/-2 Data in a small watershed. *Remote Sensing, 13*(7), 1229. https://doi.org/10.3390/rs13071229

Wiesmeier, M., Sporlein, P., Geu, U., Hangen, E., Haug, S., Reischl, A., Schilling, B., von Lutzow, M., & Kogel-Knabner, I. (2012) Soil organic carbon stocks in southeast Germany Bavaria, as affected by land use, soil type and sampling depth. *Global Change Biology, 18*(7), 2233–2245. https://doi.org/10.1111/j.1365-2486.2012.02699.x

Wubie, M. A., & Assen, M. (2020). Effects of land cover changes and slope gradient on soil quality in the Gumara watershed, Lake Tana basin of North–West Ethiopia. *Modeling Earth Systems and Environment, 6*, 85–97. https://doi.org/10.1007/s40808-019-00660-5

Wu, J. C., Xu, J. X., Yuan, S. Z., Liu, J. L., Jiang, Y. H., & Xu, J. F. (2001). Pesticide-induced susceptibility of rice to brown planthopper Nilaparvata lugens. *Entomologia Experimentalis et Applicata, 100*(1), 119-126. https://doi.org/10.1046/j.1570-7458.2001.00854.x

Yang, T., Siddique, K. H. M., & Liu, K. (2020). Cropping systems in agriculture and their impact on soil health - a review. *Global Ecology and Conservation, 23*, e01118. https://doi.org/10.1016/j.gecco.2020.e01118

Yerima, B. P. K., & van Ranst, E. (2005). *Major Soil Classification Systems used in the Tropics: Soils of Cameroon.* Trafford Publishing, Victoria, p 312.

Yimer, F., Ledin, S., & Abdelkadir, A. (2006). Soil organic carbon and total nitrogen stocks as affected by topographic aspect and vegetation in the Bale Mountains, Ethiopia. *Geoderma, 135*(4), 335-344. https://doi.org/10.1016/j.geoderma.2006.01.005

Zajícová, K., & Chuman, T. (2019). Effect of land use on soil chemical properties after 190 years of forest to agricultural land conversion. *Soil and Water Research, 14*(3), 121–131. https://doi.org/10.17221/5/2018-SWR

Zhang, J., He, N., Liu, C., Xu, L., Chen, Z., Li, Y., Wang, R., Yu, G., Sun, W., Xiao, C., Chen, H. Y. H., & Reich, P.B. (2020). Variation and evolution of C:N ratio among different organs enable plants to adapt to N-limited environments. *Global Change Biology, 26*(4), 2534-2543. https://doi.org/10.1111/gcb.14973